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ABSTRACT

The measurement of the velocity of ultrasound provides a nondestructive means to determine the specific stiffnesses of paper. Instruments have been developed at the Institute of Paper Science and Technology (IPST) to make in-plane measurements on cut samples and on moving paper webs. These instruments are described and their capabilities illustrated with representative examples. The prospect for extending these capabilities to on-machine instrumentation are reviewed.

INTRODUCTION

Research at the Institute of Paper Science and Technology has used ultrasound to make nondestructive measurement of the elastic stiffnesses which are indicators of paper product quality and can be related to various end-use specifications used in the paper industry.

The in-plane elastic stiffnesses are calculated from a measure of the velocity of ultrasound in the plane of the paper. The instrumentation developed at IPST for making in-plane measurements on cut samples are first reviewed. Then, the instrumentation to make in-plane measurements on moving paper webs is described and the capabilities illustrated with representative examples. Finally, the prospects for extending these capabilities to on-machine instrumentation are reviewed.

ROBOT-BASED IN-PLANE INSTRUMENT

IPST has conducted research on the use of ultrasound to characterize the mechanical properties of paper since the late 1970's. The early work was done with hand operated transducer holders. The transit time of the ultrasound signal from transmitter to receiver was recorded for several transducer spacings (1). The velocity was calculated by determining the slope of the distance versus the transit time data. This technique avoided the need to correct the time measurement for non-paper delays. This philosophy has been continued in subsequent instrument developments.

The first automatic instrument developed by IPST is described in detail in the literature (2). This computer-controlled instrument automatically selected the separation of the transducers and raised and lower them onto the sample. The computer determined the time-of-flight difference for the near and far transducer spacings by cross-correlation. The sample was attached to a turntable driven by a stepping motor. In addition to determining the longitudinal and shear velocities in the machine direction (MD) and the cross-machine direction (CD), this instrument could measure velocities as a function of angle from the MD. The velocity squared values (specific stiffnesses) and a "polar plot" of the results were displayed and printed.

The above instrument was superseded by a robot-based instrument (3). A Mitsubishi RM-501 robot arm with a special "end effector" was used to position the transducers in the desired orientations on the sample. The instrument could be programmed to test up to four samples positioned around the robot. New miniature bender transducers were designed for this instrument to provide greater bandwidth and modal purity and improved sensitivity. Transducers with this design continue to be used in our present instrumentation.

The present robot-based instrument uses an Adept 604-S robot. This is a four-axis robot and is more conveniently changed or modified in its positioning program than the five-axis arm of the RM-501. The same end effector and bender transducers noted above are used. Up to five 20 cm by 20 cm samples positioned around the robot or a 30 cm by 60 cm strip may be tested without operator intervention. This instrument is very versatile for in-plane ultrasonic testing and research.

IN-PLANE SYSTEM FOR MOVING WEB

The in-plane measurement system for moving webs is based on a set of wideband bimorph bender ultrasonic transducers similar to those developed for the in-plane laboratory instruments noted above. A technique was developed to adhere a metal wire or cap to the tip of the transducer to provide a more durable wear surface. The transducers are mounted in the outer wall of a 10 inch diameter aluminum cylinder in special spring-loaded holders. The cylinder is mounted in a web handling system. The transducers are oriented outward so that each active element protrudes slightly outside the circumference of the cylinder.

The transducers are used in sets of three. One transducer serves as a transmitter, and may be positioned at either end of the set or in between the two transducers used as receivers. The transducers may be oriented and aligned to operate in the longitudinal or shear mode in the MD or CD directions. For example, a transmitter positioned to excite longitudinal waves in the MD direction of the web also excites shear waves in the CD direction. Four transducers may be positioned relative to this transmitter into two sets of receivers. For both sets, the receivers are positioned at different distances (NEAR and FAR) from the transmitter in order to create a path length difference from transmitter to receivers. This path length difference is divided by the measured difference in pulse flight times for the calculation of in-plane velocities.

One receiver set, aligned in the CD direction and oriented to transmit and detect CD shear waves, has a CD NEAR distance of 46 mm and the CD FAR is 82 mm for a path length difference of 36 mm. The other set, aligned in the MD direction and oriented to transmit and detect MD longitudinal waves, has a MD NEAR distance of 66 mm and the MD FAR is 101 mm for a path length difference of 35 mm. Similarly, one may orient the transducers to make longitudinal measurements in the cross direction and shear measurements in the machine direction.

The web is wrapped part way around the cylinder. The portion of a rotation within which a set of transducers are in contact with the web is the active measurement period for that set. During this active period, the transmitter is excited by single-cycle, 80 KHz, ultrasonic pulses spaced at approximately 1 millisecond intervals. The pulse interval is just long enough to allow time for the waves propagating within the web from the previous excitation to die out. Each excitation causes the transmitter to ring for a few cycles, producing in-plane waves that propagate in all directions. The receivers convert the waves back into electrical signals which are captured by a digitizing oscilloscope. After averaging a number of waves within the active period of rotation, the oscilloscope takes time measurements of corresponding half cycle peaks. The peak times for each receiver set are subtracted and sent to the 486 computer for velocity calculations.

Pulse excitations are sent to the transmitter only during the active measurement period. A square wave generator sends a continuous train of pulses to the input of a 3-channel analog multiplexer. A 4-state roll-around counter determines which multiplexer output is addressed to the input. Two metallic targets are fixed to the cylinder. One target is positioned at the beginning of the active region to trigger an inductive proximity sensor, which clears the multiplexer/counter circuit. The other target, located at the end of the active region, clocks the counter. Excitation pulses are passed by the multiplexer to the transmitter only during the zero state of the counter. Thus, 80 KHz one cycle sine pulses are sent to the transmitter only while the transducers are in contact with the web. The signals detected by the 4 receiver transducers are captured and processed by a 4-channel digitizing oscilloscope.

The transducer housing and the carrier for mounting the transducers in the cylinder are designed to minimize variation in the contact force between the transducers and the web. Part of the housing is square in cross section and slides freely in a square hole in the carrier. This maintains the rotational alignment of the bender transducer. Relatively weak springs hold the transducer in light contact with the paper web or with the cap on the carrier when there is no paper. The caps are held in place with screws and can be removed to replace or reposition the transducers from outside the cylinder without removing the main body of the carrier.

In-plane CD shear and MD longitudinal data have been taken on rolls of paper representing a variety of commercial grades. These paper grades have included: 26, 42, and 69#/1000 sq.ft. liners; 30#/3000 sq.ft. newsprint, 26#/1000 sq.ft. medium, 70#/3300 sq.ft. coated two side free sheet, stamp paper with glue applied, and 60#/3000 sq.ft. extensible sack kraft. The data is, in general, in agreement with cut samples measured with the laboratory in-plane ultrasonic instrument.

With one transducer set positioned to measure in the CD longitudinal mode and another set positioned in the CD shear mode data may be collected with the web in light tangential contact with the cylinder. With tangential contact only one longitudinal pulse set and one shear pulse set are captured each cylinder rotation, whereas with partial wrap the transducers are in contact with the web long enough to permit measurement by averaging several pulses each cylinder rotation. The results are essentially the same, however, it may be necessary to average the data from several rotations of the cylinder to obtain good signal-to-noise data with tangential contact. With the web wrapped part way around the cylinder, good signal-to-noise data can be obtained by signal averaging within one cylinder rotation.

Provision is also included in the cylinder to mount transducer sets at ± 45 degrees to the machine direction. Two sets of transducers were mounted at ± 45 degrees and oriented to operate in the longitudinal mode. This transducer arrangement was used to take data on various rolls of paper.

The two measurements at ± 45 degrees are not sufficient to determine the polar angle (the angle of the direction of maximum stiffness relative to the MD), but do provide an indication of the in-plane stiffness alignment relative to the machine direction. The squared velocity ratio,

$$(V_{+45})^2/(V_{-45})^2),$$

or the difference divided by the average,

$$\frac{2[(V_{+45})^2 - (V_{-45})^2]}{[(V_{+45})^2 + (V_{-45})^2]}$$

may be used to infer the direction of maximum stiffness relative to the MD.

In-plane polar specific stiffness measurements are now routinely performed on cut samples in the laboratory, wherein velocity readings are recorded every 5 or 10 degrees. The polar stiffness plot is normally in the shape of a peanut, but the polar velocity plot may be closely approximated by an ellipse at angles away from the vicinity of the CD. Since any ellipse may be uniquely defined by three distinct points, two points at ± 45 degrees and one point in the MD (zero degrees) are sufficiently removed from the CD to define an ellipse. This ellipse provides a good approximation to the standard polar test for both polar angle and area. This illustrates the type of data collection that could be implemented on-line.

The cylinder described above depends upon partial wrap and friction contact with the web in order to move at web speed. A system which would drive the above cylinder at web speed would have advantages over a friction driven system. A synchronous system would place no inertial load on the web. Therefore, it may be useable with very thin papers. In addition, transducer life should be much longer, since the transducers would not be abraded by a possible web-to-transducer speed difference.

Synchronously Driven Wheels

The cylinder system with a partial wrap is appropriate for use with narrow webs. However, this system would not be useable in a scanning system for wider webs. The partial wrap system would be limited to applications where it is practical to use multiple transducer sets in a cylinder with a length greater than the width of the web. The following describes apparatus which provides the required interface of the transducers to a moving web in an embodiment suitable for scanning across a wide web.

This system includes three wheels, nominally 25 mm wide and 160 mm in diameter. The three wheels are positioned to contact the web tangentially, with two wheels placed above or on one side of the web and the third wheel placed below or on the other side of the web. The contact point of the third wheel is in line and preferable between the contact points of the two wheels above the web.

Each of the transducer wheels is driven by a servo motor with a control system to maintain rotational synchronization of the wheels. An encoder is used to measure the speed of the web as input to the control system to match the speed of the transducer wheels to the speed of the web.

Two wideband bimorph bender ultrasonic transducers, the same or similar to those described above, are mounted in each wheel in special spring-loaded carriers. The transducers are mounted 180 degrees apart within each wheel, with one transducer oriented to produce/receive longitudinal waves in the direction of rotation (MD) and the other oriented for shear waves. The transducers are mounted so that each active element protrudes slightly outside the circumference of the wheel. The spring loading is designed to minimize the variability in the contact force between the transducers and the web.

The synchronous system may be mounted on an O-frame or C-frame instrument platform for cross-web scanning -- something not possible with a wrapped cylinder. Provision may be made to bring the transducers into or out of contact with the web by an appropriate extension/retraction mechanism. This permits the system to be scanned over the web from an off-web position, and then extended to contact the web with the wheels rotating at web speed.

The drive system functions such that the longitudinal-oriented transducers in the three wheels are in contact with the web simultaneously during rotation, and the three shear-oriented transducers are in contact simultaneously one-half of a rotation later. The drive system matches the speed of the web without loading the web.

In the configuration described here, the pass line is maintained by having wheels on both sides of the web. This provides good transducer contact with the web even though web tension may decrease near the edges.

One could add two wheels to the shaft of one of the wheels. Two sets of three transducers could then be aligned on opposite sides of this wheel set. These would enable one to make CD shear and CD longitudinal velocity measurements. In addition, MD longitudinal and MD shear velocities could be measured, and the web pass line is maintained while scanning.

However, it is only necessary to measure two of the following three: the CD longitudinal velocity (V_{CD}), the MD longitudinal velocity (V_{MD}), and the shear velocity (V_{SH}). The third velocity can be calculated using the relationship (1),

$$(V_{SH})^2 = 0.387\ (V_{MD})(V_{CD})$$

Since the shear velocity (V_{SH}) should be the same whether measured in CD or MD, both the longitudinal velocity and the shear velocity are measured in the MD and the CD longitudinal velocity is calculated using the above relationship,

$$V_{CD} = 2.58\,(V_{SH})^2/V_{MD}.$$

By making both longitudinal and shear velocity measurements in the MD, sensitivity to short range CD variations should be increased.

A third configuration would provide on-line determinations of the in-plane polar specific stiffness. This would involve the addition of two wheels to the shaft of one of the wheels, as mentioned above, with the added transducers oriented at ± 45 degrees to the MD. A transmitter on the lower wheel would be positioned such that the angle between it and each outer transducer would also be ± 45 degrees. These two 45 degree measurements and the MD longitudinal measurement would determine three points to define an ellipse. This would allow nondestructive, on-line determination of polar stiffness values, such as, polar angle and area.

The synchronous "three-wheel" configurations described above continue the use of transducers in sets of three. This provides velocity measurement by determining the transit time difference over different distances. It may be possible to simplify the hardware required, for example, no transducers in the bottom wheel. The system would then use transducers in sets of two (transmitter and receiver). A technique to calibrate for time delays in the circuitry would be required. The tradeoffs involved remain to be explored.

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